

# No Evidence for Dark Energy Dynamics from a Global Analysis of Cosmological Data

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We use a variant of principal component analysis to investigate the possible temporal evolution of the dark energy equation of state,  $w(z)$ . We constrain  $w(z)$  in multiple redshift bins, utilizing the most recent data from Type Ia supernovae, the cosmic microwave background, baryon acoustic oscillations, the integrated Sachs-Wolfe effect, galaxy clustering, and weak lensing data. Unlike other recent analyses, we find no significant evidence for evolving dark energy; the data remains completely consistent with a cosmological constant. We also study the extent to which the time-evolution of the equation of state would be constrained by a combination of current and future-generation surveys, such as Planck and the Joint Dark Energy Mission.

## 1 Introduction

One of the defining challenges for modern cosmology is understanding the physical mechanism responsible for the accelerating expansion of the Universe<sup>1,2</sup>. The origin of the cosmic acceleration can be due to a new source of stress-energy, called “dark energy”, a modified theory of gravity, or some mixture of both<sup>3</sup>.

In the absence of a well-defined and theoretically motivated model for dark energy, it is generally assumed that the dark energy equation of state (the ratio of pressure to energy density) evolves with redshift with an arbitrary functional form. Common parameterizations include a linear variation,  $w(z) = w_0 + w_z z$ <sup>4</sup>, or an evolution that asymptotes to a constant  $w$  at high redshift,  $w(z) = w_0 + w_a z/(1+z)$ <sup>5,6</sup>. However, given our complete ignorance of the underlying physical processes, it is advisable to approach our analysis of dark energy with a minimum of assumptions. Fixing an ad hoc two parameter form could lead to bias in our inference of the dark energy properties.

In this paper we measure the evolution history of the dark energy using a flexible and almost completely model independent approach, based on a variant of the principal component analysis (PCA) introduced in Huterer (2003)<sup>7</sup>; in order to be conservative, we begin by using data we determine the equation only from geometric probes of dark energy, namely the cosmic microwave background radiation (CMB), Type Ia supernovae (SNe) and baryon acoustic oscillation data (BAO). We perform a full likelihood analysis using the Markov Chain Monte Carlo approach<sup>8</sup>. We then consider constraints on  $w(z)$  from a larger combination of datasets, including probes of the growth of cosmological perturbations, such as large scale structure (LSS) data. An important consideration for such an analysis is to properly take into account dark energy perturbations, and we make use of the prescription introduced in<sup>9</sup>. This method implements a Parameterized Post-Friedmann (PPF) prescription for the dark energy perturbations following<sup>10</sup>.

## 2 Analysis and results

The method we use to constrain the dark energy evolution is based on a modified version of the publicly available Markov Chain Monte Carlo package CosmoMC<sup>8</sup>, with a convergence diagnostics based on the Gelman-Rubin criterion<sup>12</sup>. We consider a flat cosmological model described by the following set of parameters:

$$\{w_i, \omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s]\} , \quad (1)$$

where  $\omega_b$  ( $\equiv \Omega_b h^2$ ) and  $\omega_c$  ( $\equiv \Omega_c h^2$ ) are the physical baryon and cold dark matter densities relative to the critical density,  $\Theta_s$  is the ratio of the sound horizon to the angular diameter distance at decoupling,  $\tau$  is the optical depth to re-ionization, and  $A_s$  and  $n_s$  are the amplitude of the primordial spectrum and the spectral index, respectively. We bin the dark energy equation of state in five redshift bins,  $w_i(z)$  ( $i = 1, 2, \dots, 5$ ), representing the value at five redshifts,  $z_i \in [0.0, 0.25, 0.50, 0.75, 1.0]$  and, for  $z > 1$ , we fix the equation of state parameter at its  $z = 1$  value, since we find that current data place only weak constraints on  $w(z)$  for  $z > 1$ . To summarize, our parameterization is given by:

$$w(z) = \begin{cases} w(z = 1), & z > 1; \\ w_i, & z \leq z_{max}, z \in \{z_i\}; \\ \text{spline}, & z \leq z_{max}, z \notin \{z_i\}. \end{cases} \quad (2)$$

Finally, we follow<sup>11</sup> to determine uncorrelated estimates of the dark energy parameters. For the CMB, we use data and likelihood code from the WMAP team's 5-year release<sup>13</sup> (both temperature TT and polarization TE; we will refer to this analysis as WMAP5). We also checked that results don't change if we use the latest data release from WMAP<sup>14</sup>. Supernova data come from the Union data set (UNION) produced by the Supernova Cosmology Project<sup>15</sup>; however, to check the consistency of our results, we also used the recently released Constitution dataset (Constitution)<sup>18</sup> which, with 397 Type Ia supernovae, is the largest sample to date. We also used the latest SDSS release (DR7) BAO distance scale<sup>16,17</sup>. Weak lensing (WL) data are taken from CFHTLS<sup>22</sup> and we use the weak lensing module provided in<sup>19,20</sup>, with some modifications to assess the likelihood in terms of the variance of the aperture mass (Eq. 5 of<sup>22</sup>) with the full covariance matrix<sup>21</sup>. The cross-correlation between CMB and galaxy survey data is employed using the public code at<sup>23</sup>. We modify it to take into account the temporal evolution of the dark energy equation of state, since the code only considers  $w$ CDM cosmologies. We refer to<sup>24,25</sup> for a description of both the methodology and the datasets used. Finally, we use the recent value of the Hubble constant from the SHOES (Supernovae and  $H_0$  for the Equation of State) program,  $H_0 = 74.2 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1} (1\sigma)$ <sup>26</sup>. We also incorporate baryon density information from Big Bang Nucleosynthesis  $\Omega_b h^2 = 0.022 \pm 0.002 (1\sigma)$ <sup>27</sup>, as well as a top-hat prior on the age of the Universe,  $10 \text{ Gyr} < t_0 < 20 \text{ Gyr}$ .

As we can see from Fig. 1, all values are compatible with a cosmological constant ( $w = -1$ ) at the  $2\sigma$  level; in particular, there is no discrepancy between the Union and Constitution datasets. Moreover, as we can see from Fig. 2, the addition of cosmological probes of cosmic clustering noticeably reduces the uncertainty in the determination of the dark energy parameters, especially at high redshifts.

To reinforce our conclusions, we also created several mock datasets for upcoming and future SN, BAO, and CMB experiments. The quality of future datasets allows us to constrain the dark energy evolution beyond redshift  $z = 1$ . We thus consider an additional bin at  $z = 1.7$ , with a similar constraint:  $w(z > 1.7) = w(z = 1.7)$ . We consider a mock catalog of 2,298 SNe, with 300 SNe uniformly distributed out to  $z = 0.1$ , as expected from ground-based low redshift samples, and an additional 1998 SNe binned in 32 redshift bins in the range  $0.1 < z < 1.7$ , as

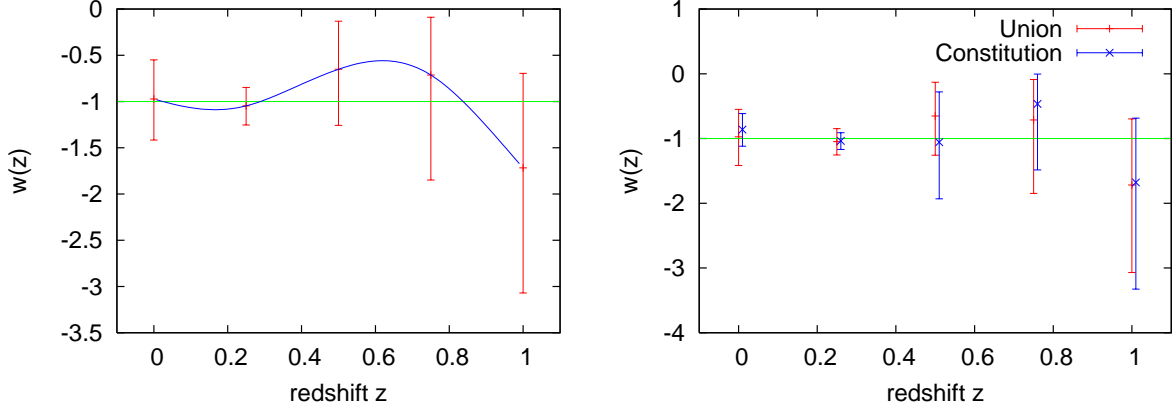


Figure 1: Left: uncorrelated constraints on the dark equation of state parameters using WMAP+UNION+BAO. Right: comparison between WMAP+UNION+BAO and WMAP+Constitution+BAO; the points for the Constitution dataset have been slightly shifted to facilitate comparison between the two cases: we find no significant difference between UNION and Constitution.

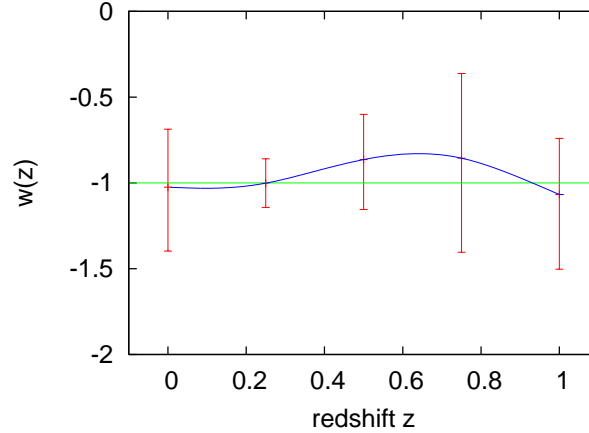


Figure 2: Results using data from a “global” dataset which includes WMAP+UNION+BAO+WL+ISW+LSS; error bars are at  $2\sigma$ .

expected from JDEM or similar future surveys<sup>28</sup>. The error in the distance modulus for each SN is given by the intrinsic error,  $\sigma_{\text{int}} = 0.1$  mag. In addition, we use a mock catalog of 13 BAO estimates, including 2 BAO estimates at  $z = 0.2$  and  $z = 0.35$ , with 6% and 4.7% uncertainties (in  $D_V$ ), respectively, 4 BAO constraints at  $z = [0.6, 0.8, 1.0, 1.2]$  with corresponding fiducial survey precisions (in  $D_V$ ) of [1.9, 1.5, 1.0, 0.9]% (V5N5 from<sup>29</sup>), and 7 BAO estimates with precision [0.36, 0.33, 0.34, 0.33, 0.31, 0.33, 0.32]% from  $z = 1.05$  to  $z = 1.65$  in steps of 0.1<sup>30</sup>.

We simulate Planck data using a fiducial  $\Lambda$ CDM model, with the best fit parameters from WMAP5, and noise properties consistent with a combination of the Planck 100–143–217 GHz channels of the HFI<sup>31</sup>, and fitting for temperature and polarization using the full-sky likelihood function given in<sup>32</sup>. In addition, we use the same priors on the Hubble parameter and on the baryon density as considered above. As can be seen from Table 1 and Figure 3, future data will reduce the uncertainties in  $w_i$  by a factor of at least 2, with the relative uncertainty below 10% in all but the last bin (at  $z = 1.7$ ).

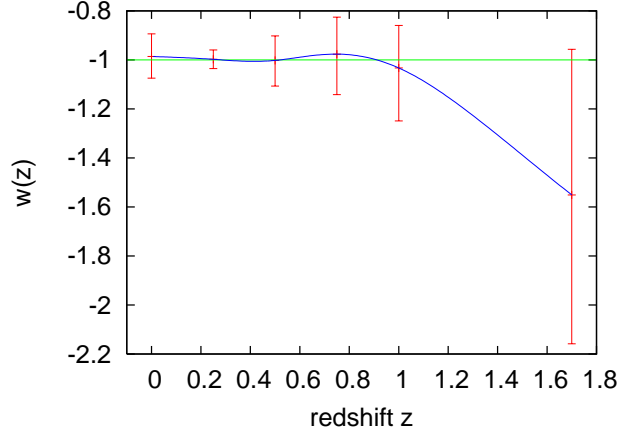


Figure 3: Uncorrelated constraints on the dark energy equation of state parameters, for mock datasets from Planck and JDEM; error bars are at  $2\sigma$ .

### 3 Conclusions

One of the main tasks for present and future dark energy surveys is to determine whether or not the dark energy density is evolving with time.

We have performed a global analysis of the latest cosmological datasets and have constrained the dark energy equation of state using a very flexible and almost model independent parameterization. We determine the equation of state  $w(z)$  in five independent redshift bins, incorporating the effects of dark energy perturbations. We find no evidence for a temporal evolution of dark energy—the data is completely consistent with a cosmological constant. This agrees with most previous results, but significantly improves the overall constraints. We show that future experiments, such as Planck or JDEM, will be able to reduce the uncertainty on  $w(z)$  to less than 10% in multiple redshift bins, thereby mapping any temporal evolution of dark energy with high precision. With this data it will be possible to measure the temporal derivative of the equation of state parameters,  $dw/dz$ , useful in discriminating between two broad classes of “thawing” and “freezing” models<sup>33</sup>.

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